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Source rupture process inversion of the 2013 Lushan earthquake, China

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Abstract: The spatial and temporal slip distribution of the Lushan earthquake was estimated using teleseismic body wave data. To perform a stable inversion, we applied smoothing constraints and determined their optimal relative weights on the observed data using an optimized Akaike's Bayesian Information Criterion (ABIC). The inversion generated the source parameters. Strike, dip and slip were 218°, 39° and 100.8°, respectively. A seismic moment (M_0) was 2.1×10^{20} Nm with a moment magnitude (Mw) of 6.8, and a source duration was approximately 30 second. The rupture propagated along the dip direction, and the maximum slip occurred at the hypocenter. The maximum slip was approximately 2.1 m, although this earthquake did not cause an apparent surface rupture. The energy was mainly released within 10 second. In addition, the Lushan earthquake was apparently related to the 2008 Wenchuan earthquake. However, the question of whether it was an aftershock of the Wenchuan earthquake requires further study.

Key words: source rupture process; teleseismic wave; Lushan earthquake

1 Introduction

On April 20, 2013 (UTC 00:02:48), a major earthquake with magnitude of *M*7.0 occurred in Lushan county, Sichuan province. This earthquake was the largest seismic event since the 2008 Wenchuan earthquake in this area and caused more than 190 human deaths and injured millions of people. The China Earthquake Administration determined that the epicenter was at 30.284° N and 102.955° E at a shallow depth of 12.3 km. The mainshock was followed by hundreds of aftershocks, the largest of which was *M*5.4.

The study area is located in the eastern margin of the Tibetan Plateau. Tectonically, this area belongs to the intersection of the Songpan-Ganzi block (SP-GZ block) and the Sichuan basin (SC basin). The main active faults in this area are the Longmenshan fault (LMS fault), Xianshuihe fault (XSH fault), and Anninghe fault (ANH fault). The Lushan earthquake occurred on the Longmenshan fault, which is also the seismogenic fault of the 2008 Wenchuan earthquake. The Longmenshan fault is a NE-striking fault, starting at Luding, passing through Maowen, Beichuan, and Guangyuan, terminating near Mianxian. And the length and width are approximately 500 km and 30 – 40 km, respectively. The fault can be divided into three segments: the segment from Beichuan to Mianxian is the northeastern part, the section from Beichuan to Dujiangyan comprises the middle segment, and the reach from Luding to Kangding constitutes the southwestern segment (Fig. 1). Since the Cenozoic Era, the Longmenshan fault has remained active, and GPS monitoring has

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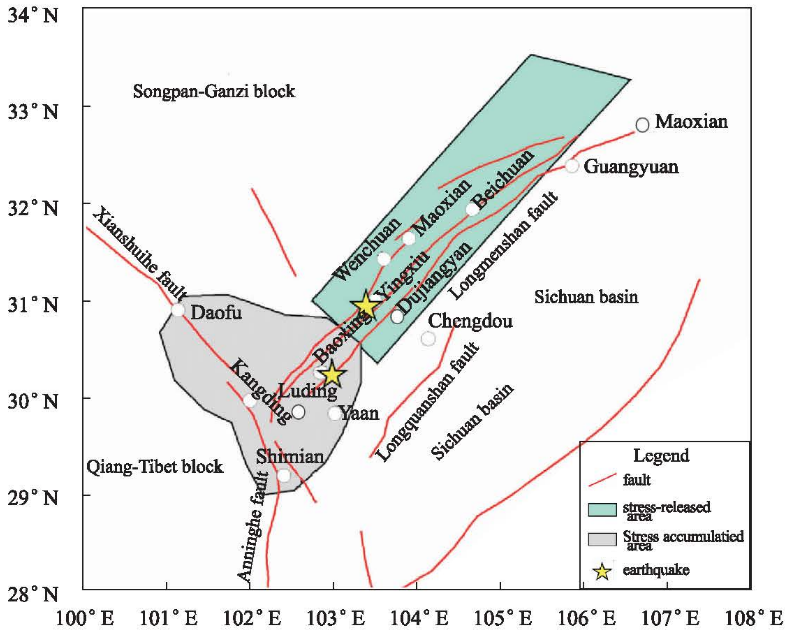


Figure 1 Geotectonic setting and schematic map showing the location of the geostress measurement sites

shown that the middle and southwestern segments are more active than the northern part. The intersection of the Longmenshan, Xianshuihe and Anninghte faults is an earthquake-prone region, which deserves further study[1].

The purpose of this study was to estimate the source rupture process of the Lushan earthquake and preliminarily discussed the relationship with the 2008 Wenchuan earthquake.

2 Methodology and data

Earthquake source process is used to determine the physical behavior of an earthquake. Using kinematic source rupture process inversion, we can obtain an understanding of the coseismic slip distribution. In general, seismic sources can be modeled as point or finite fault sources. Point source modeling is suitable for representing small earthquakes, because its size approaches zero, the magnitude is small with a short duration and the slip is assumed to be uniform. For large earthquakes, however, we should consider the spatiotemporal variation of the slip distribution. Therefore, finite fault model is appropriate, which can be approximated by multiple point sources. A fault plane is divided into many subfaults, where a point source is located at the gravity center of each subfault. In addition, each point source may have a different source time function $\Delta(t)$ or moment rate function $M(t)$. The displacement caused by multiple point sources on a finite fault is

$$U_n(x,t) = \sum_{i=1}^{N} \hat{U}_n^i(x,\xi_i,t)\Delta\dot{U}^i(\xi_i,t) \tag{1}$$

where $U_n(x,t)$ is the displacement in time and space, N is the total number of point sources, $\Delta\dot{U}^i(\xi_i,t)$ is the time derivative of the fault slip history for i-th point source located at ξ and $\hat{U}_n^i(x,\xi_i,t)$ is the displacement caused by one unit fault slip for the i-th point source located at ξ.

Here, we used teleseismic body wave data to estimate the source rupture process of the Lushan earthquake. In general, teleseismic body waves contain information on the overall moment release rate and depth range of the rupture area, whereas near-source waveforms contain detailed information on the source area. Therefore, to obtain a detailed and stable source process, it is preferable to use both teleseismic body wave data and near-source data[2]. However, after a large earthquake, it is difficult to obtain strong ground motion data within a short period of time. Therefore, in this study, only teleseismic wave data were used for the inversion to derive the preliminary source process.

We retrieved teleseismic body wave data recorded at

IRIS-DMC stations via the Internet. A total of 43 teleseismic stations with 129 records were selected based on the criteria of a good azimuthal coverage and a high signal-noise ratio. The locations of the seismograph stations are shown in figure 2. To avoid the contamination of the Earth's structure, such as complexities in the upper mantle, the epicenter distance ranged from 30° to 90°[3]. In addition, the teleseismic body waves were windowed for 60 second, starting 10 second before the P-wave arrival, band-pass filtered between 0.001 and 1.0 Hz and then integrated into a displacement with a sampling time of 0.25 second. For the Green's function, we adopted the method of Kikuchi and Kanamori[4].

3 Results

3.1 Inversion parameters

Assuming that the earthquake occurred on a single fault plane, we constructed the fault plane according to the aftershock distribution within 4 days after the mainshock (Fig. 3). The fault plane dimension is 65 km × 35 km, and after a repeated trial and error process, the subfault dimension was determined to be 5 km × 5 km. Thus, the grid number of 91 was used in the inversion. In addition, we adopted the geometry of the

Figure 2 Teleseismic station distribution map (Stars represent the epicenter of the main shock. The map is drawn on an azimuthal equidistant projection)

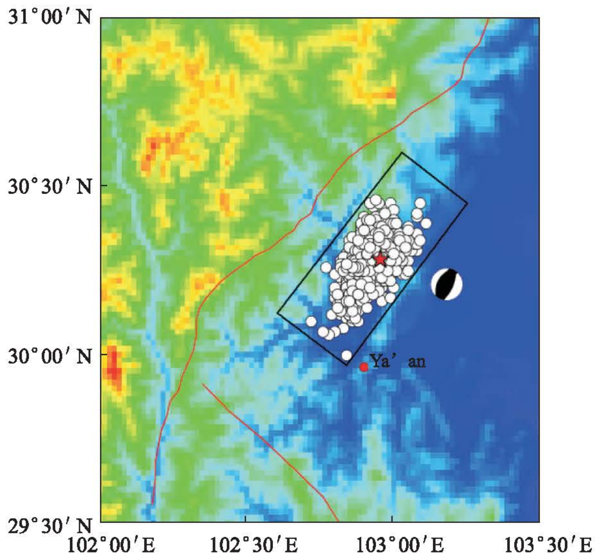


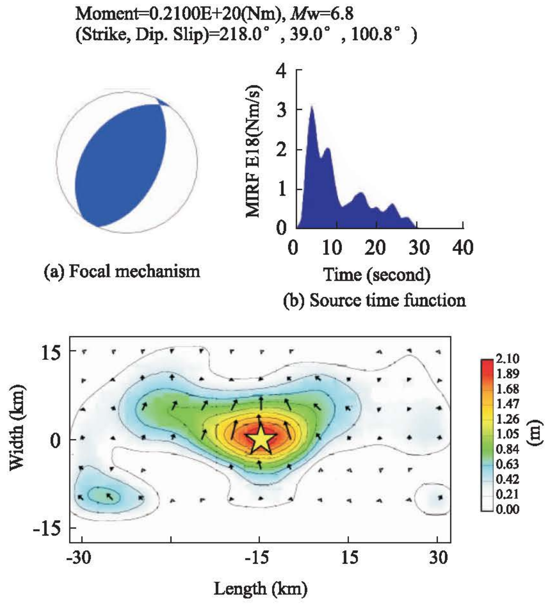
Figure 3 Earthquake distribution and fault model of the Lushan earthquake

focal mechanism obtained from the USGS Wphase Moment Solution (strike, dip, rake) = (218°, 39°, 103°) using the epicenter determined by the USGS (latitude = 30.284°; longitude = 102.955°). We set the focal depth to be 12.3 km, and the slip rate function of each subfault was expanded into a series of 18 triangular functions with a rise time of 1 second. We also examined the optimum value for the rupture velocity *Vr* within the range of 0.5 km/second to 3.5 km/second, and found when the maximum rupture velocity was 3.0 km/second, a minimum variance was obtained. The rigidity surrounding the fault plane was assumed to be μ = 33.33 GPa based on the structure model.

3.2 Source rupture process

The inversion results are shown in figures 4 and 5. Figure 4(a) illustrated that the earthquake focal mechanism was thrust faulting, and the strike, dip angle and rake angle were 219°, 35° and 100.8°, respectively. The final dislocation (Fig. 4(c)) indicated that the rupture propagated mainly along the dip direction from the hypocenter to a shallower region, and the maximum slip of 2.1 m occurred at the hypocenter. In the shallower part, the slip ranged from 0.2 to 0.6 m. The rupture extended laterally in the range of 20 km from the hypocenter to both sides. Based on the slip distribution, it was readily determined that a surface rupture was not apparent, which is one reason why the damage caused by the Lushan earthquake was not as serious as that of the Wenchuan earthquake. The source time function (Fig. 4(b)) indicated that a total seismic moment M_0 of 2.1×10^{20} Nm (*M*w 6.8) was released over a period of 30 second. The majority of the energy was released within 10 second after the earthquake initiated. An additional energy release occurred within 20 second, which may have been a strong aftershock. By comparison, the overall features obtained by our inversion were in accordance with the results of other researchers[5,6]. Minor differences between the obtained maximum slip values may be attributed to differences in the velocity models and inversion methods. The waveform-fitting results indicated that most of the theoretical seismograms fit well with the observed waveforms (Fig. 5), thereby supporting the reliability and robustness of our results.

Figure 6 represents a map view of the slip distribution and a rupture time history as well as snapshots of the slip rate at two-second intervals. The source rupture process obtained can be divided into two stages. At stage one, the rupture nucleated near the hypocenter and then propagated along the dip direction during four to eight second after the initial break. At this stage, the total maximum slip was 2.1 m. At stage two, the rupture continuously propagated to the shallower part with a slip ranging from 0.2 to 0.8 m; this phase corresponds to the energy release stage.



(a) Focal mechanism (b) Source time function (c) Slip distribution

Figure 4 Inversion results for the Lushan earthquake

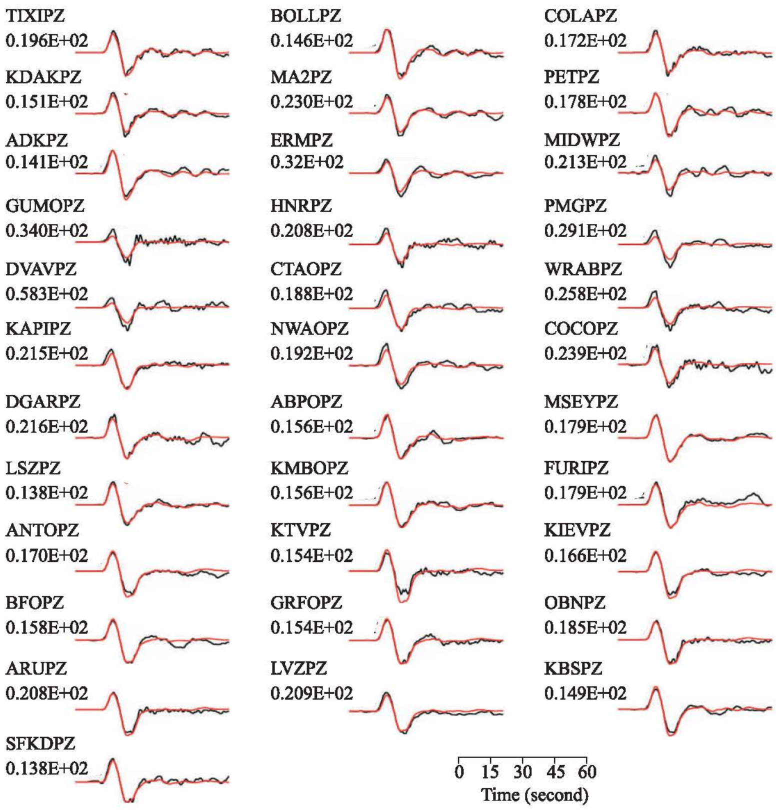


Figure 5 Comparisons of the observed waveforms (black curve) with the theoretical seismograms (Red curve)

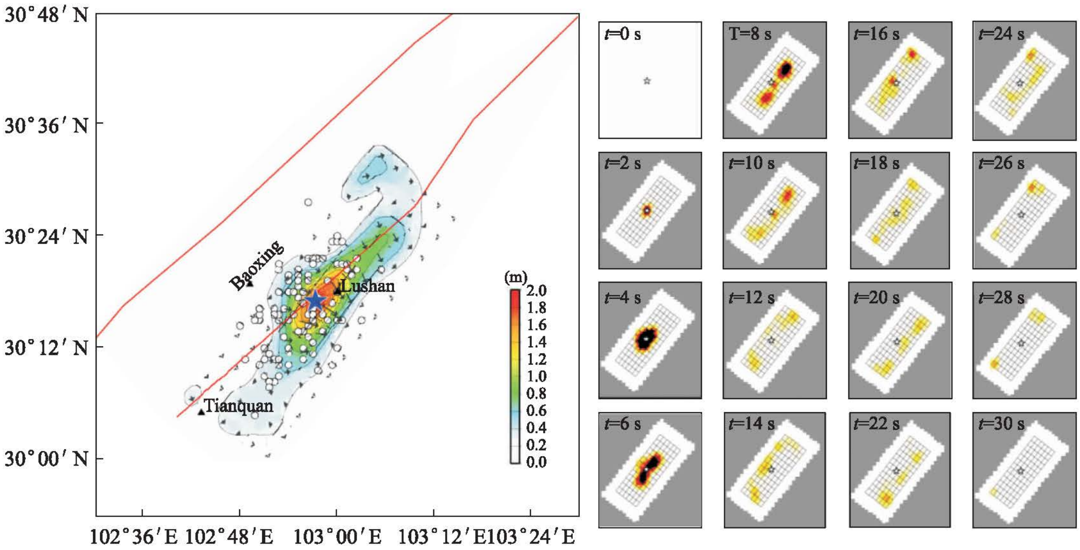


Figure 6 Surface projection of the fault slip distribution and snapshots of the slip at two-second intervals (Red lines indicate the active faults, and a blue star denotes the epicenter)

4 Conclusions and discussion

By performing an inversion, we estimated the slip distribution of the Lushan earthquake. To perform a stable inversion, we applied smoothing constraints and determined their relative weights on the observed data using ABIC criterion. Assuming that the earthquake occurred on along single fault plane, we constructed a fault model according to the aftershock distribution. The inversion results showed a total seismic moment of $Mo = 2.1 \times 10^{20}$ Nm, and a moment magnitude of $Mw = 6.8$ with a total maximum slip of 2.1 m at 12 km. The source rupture duration of this earthquake was approximately 30 second. The rupture nucleated around the hypocenter and propagated mainly along the dip direction.

After the Lushan earthquake, some researchers argued that this event was an aftershock of the Wenchuan earthquake, whereas others presented different opinions. Based on the location, the Lushan earthquake occurred in close proximity to the Wenchuan earthquake. The former occurred on the southwestern segment of the Longmenshen fault, whereas the latter occurred on the middle segment. The 2008 Wenchuan earthquake caused a substantial surface rupture, which mainly propagated in a northerly direction along the Longmenshen fault. However, a surface rupture caused by the Lushan earthquake was not apparent, and accordingly, the damage was not as severe as that of the Wenchuan earthquake. Although the focal mechanisms of the two earthquakes were identical, the question of whether the Lushan earthquake was the aftershock of the Wenchuan earthquake continues to be debated and requires further verification.

According to some studies, in the past, the southwestern part of Longmenshen fault was comparably stable, and large earthquakes were rare in this area. Nevertheless, since the 2008 Wenchuan earthquake, the fault has become increasingly unstable. Certain results have shown that in the southwestern segment of Longmenshen fault, and in the Kangding area in particular, the stress has accumulated to a high level, and the maximum horizontal principal stress has reached the lower limit of the yield stress. This finding means that the fault has reached a critical status. Comprehensive analyses of the seismicity and geologic materials have shown a potential for earthquakes in the southwestern part of Longmenshen fault, which warrants a further attention[1,7,8]. Based on this present work, we conclude that stress release along the southwestern segment may cause the Lushan earthquake.

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